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Tests of Light Transmission through PVC extrusions

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I have performed some measurements of light transmission through a PVC cell containing liquid scintillator and wavelength shifting (WLS) fiber with a PMT and APD detector. The results are presented here.

The light transmission of PVC has been measured using a cell of a 48ft. 4.1cm X 2.2cm ID extrusion from Plastic Extrusion Technology (PET). The cell had a loop of 0.8mm Kuraray Y-11 200ppm WLS fiber installed. The entire length of the tube was wrapped in 6mil black plastic garbage bags. A small opening measuring 2cm X 4cm was cut into the bag and masked off with black electrical tape.

The light transmission was measured by coupling the end of the fiber in the cell to a calibrated Quanticon PMT, for high sensitivity, and also to a NOνA standard APD running at a gain of 100.

The light transmission was measured under many conditions: darkness, ambient light, and intense light, and several different light sources. The ambient light was supplied by the overhead lighting in the University of Minnesota MINOS Module lab, using Phillips Alto F32T8/TL841, a 32W 4100K color temperature light, 2m above the cell. To provide the intense light, a fluorescent lamp was used, a 6400K color temperature 13W bulb made by Regent, and available at your local Menards. This lamp, known as the "Leon Light" in MINOS was specially chosen for finding leaks in the MINOS modules due to its awful (to this human's eyes) blue light emitted. The response of the fiber to this light is much greater than any other lamp tested. Many lamps tested showed almost no measurable signal, due to their reddish output. (Maybe we should just light the whole area with red LEDs. Unfortunately, I don't think this idea will work, read on to find out why.)

Two types of PVC were also tested, the original PET-Prime formulation, and the PET-B baseline formulation. The additional layers of PVC were cut from the outer skin of other extrusions from PET. The additional layers had an exposed area half that of the initial hole, 4cm^2.

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Transmission tests with PET-Prime extrusions

PMT tests.

Condition	Current	Light-Dark
Dark (2x4cm hole covered)	0.12 μA	0 μA
Ambient light	20.0 μA	19.9 μA
Intense light	1030 μA	1030 μA
Intense light +1 layer PVC	0.5 μA	0.4 μA
Intense light +2 layers PVC	0.12μA	0 μA

The PMT has a gain of 10pC/pe. Therefore a current of 1uA corresponds to 10^5pe/s leakage for a detector with PMT quantum efficiency. The leakage of ~20 μA for ambient light translates to 2MHz of photoelectons in 8cm^2, and the intense light of 100MHz.

The attenuation of the extra layer of PVC is simply the ratio of the light-dark values divided by a factor of 2 due the additionally masked area: 1030/0.4/2=1250. The attenuation length, λ, is given by: $\lambda = t/\ln(A)$, where t is the thickness of the PVC, 1.34mm, and A is the attenuation factor, 1250. The measured light attenuation length of the PET-Prime PVC is therefore 0.19mm.

APD tests

Condition	Current	Light-Dark
Dark (2x4cm hole covered)	1.0 nA	0 nA
Ambient	1.4 na	0.4 nA
Intense light	17.4 nA	16.4 nA
Intense light +1.5mm PVC	1.0 nA	0 nA

The APD has a gain of 100e/pe, so a current of 1nA is a photocurrent of 6E7pe/s. The ambient light value is a leakage of 24MHz, and the intense light value corresponds to 1GHz of leakage in the 8cm^2 area. Comparing this to the PMT value of 100MHz is simple. If you use the approximate QE ratio of 10, they are completely consistent. The ambient light leak rate would be 25MHz/8cm^2, or 3.1MHz/cm^2.

A typical APD pixel has a dark current of about 60pA at M=100. This is 0.6pA of photocurrent, or 4MHz of single pe signals. If we assume that the exposed are of a typical cell is 2*4cm*15cm. (I pessimistically assume there will be bad gluing, or leakage along the edge). This is 120cm^2 per cell, and would induce a 400MHz leak signal in ambient light. If we want to attenuate it to a level of 0.1MHz, we would need 8.3 attenuation lengths, or 1.6mm thicker PVC, to bring the total to 3.0mm. It is actually somewhat worse than this, since the measurement here was done 2m into the module, there is extra fiber attenuation, so we don't see the full effect of the leak in this test.

Therefore we would probably want to go one or 2 extra PVC attenuation lengths, up to 3.3 or 3.5mm to make the manifold end sufficiently opaque.

Along the edge of the outside modules, the problem most severe due to the large area. The module is 15m long, assuming an average attenuation factor from the WLS fiber of about 3, this corresponds to an exposure of 6cm*1500cm/3=3000cm^2. That would create a leak rate of 9300MHz, requiring 11.5 attenuation lengths (2.2mm), a total thickness of 3.5mm, or about 20 attenuation lengths to reduce it to 0.1MHz.

Additional Tests with PET-B extrusions

An additional round of testing was performed with PET-B extrusions to measure the attenuation length. The test was performed by measuring the current in the same PMT used previously. The fiber and scintillator was inside a PET-Prime extrusion with the additional layer of plastic. The bare sample was in the bare 2cmx4cm hole to measure the baseline with no attenuation. The samples labeled B are from a PET-B extrusion, samples 1 and 2 are from the outer faces, while samples 3 and 4 are from the inside web. Sample A is a new measurement from an old PET-Prime extrusion. The thicknesses were measured with a micrometer.

Sample	thickness(mm)	Dark Current (uA)	Light Current (uA)	Light-Dark in 4cm^2	Attenuation factor	Attenuation length (mm)
bare	0	0.08	1400	699.96		
A1	1.3462	0.08	0.16	0.08	8749.5	0.148313
B1	1.3716	0.08	0.28	0.2	3499.8	0.168079
B2	1.6002	0.08	0.12	0.04	17499	0.163789
B3	1.3462	0.08	0.2	0.12	5833	0.155248
B4	1.27	0.08	0.23	0.15	4666.4	0.150329

The PET-B extrusion samples show a slightly shorter attenuation length than the PET-Prime. In the previous tests of the PET-Prime sample the attenuation length was measured to be longer, 0.18mm. The measured attenuation lengths are 0.15 and 0.17. Using the longer attenuation length as a conservative estimate for the attenuation length we would need about 20 attenuation lengths to achieve sufficient opacity. This would be 3 to 3.4mm, or most pessimistically 3.8mm with the 0.19mm attenuation length. The verticals would probably be thick enough, but the horizontal modules at 3mm are unlikely to be thick enough to not need additional light blocking measures.

PVC Attenuation Conclusions

It appears that the amount of light that leaks through thin walled (~1.5mm) extrusions would make it impossible to operate the detector without additional coverage of some sort. It also appears that increasing the thickness to 3.0mm and 4.5mm would only be guaranteed to be sufficient for the 4.5mm thick extrusions. The minimum thickness would be 3.0mm, if the measured attenuation length is correct. Variations in thickness may also cause problems since it is an exponential attenuation, a slightly thin spot will yield a large light leak.

Light Source Sensitivity

Warning, this first section, shows initial qualitative results presented below, please forgive the ludicrous precision of the numbers. The next section will attempt to quantify things for comparisons.

I also tested several different light sources for their effectiveness for finding light leaks and to compare to light levels. The standard screw base devices were tested in a reflective trouble-light type housing (60W incandescent, 26W CF, 75 incandescent black-light). These and the others were measured in contact with the extrusion, or a close as was possible to get it to the opening in the black plastic. The most surprising (at least to me) result was that there was an observable response to a RED laser pointer and a red LED.

Lamp	Dark	light	light-dark	rel
Leon (13W fluorescent 6200K color temp)	0.08	1400	1399.92	93.82841823
fluor tube in contact	0.08	432	431.92	28.94906166
60W incandescent	0.08	400	399.92	26.80428954
Blue LED 50ma	0.05	200	199.95	13.40147453
26W CF	0.08	195	194.92	13.06434316
Blue LED 25ma	0.05	100	99.95	6.699061662
Flashlight (2D)	0.08	70	69.92	4.686327078
60W bug-light	0.05	64	63.95	4.286193029
AA Maglight	0.05	35.5	35.45	2.376005362
fluor tube 4100K color temp @2m	0.08	15	14.92	1
indirect sun	0.08	10.8	10.72	0.71849866
75W incandescent black-light	0.05	6	5.95	0.398793566
red laser2 (new)	0.05	2.2	2.15	0.144101877
weak sun	0.08	1.1	1.02	0.068364611
red laser1 (old)	0.08	0.5	0.42	0.028150134
Green LED 75ma	0.05	0.42	0.37	0.024798928
Green LED 50ma	0.05	0.4	0.35	0.023458445
Green LED 25ma	0.05	0.25	0.2	0.013404826
Red LED 50ma	0.05	0.22	0.17	0.011394102
Red LED 80ma	0.05	0.2	0.15	0.010053619
redled25ma	0.05	0.16	0.11	0.007372654
4W UV lamp 254nm	0.05	0.11	0.06	0.004021448
4W UV lamp 365nm	0.05	0.11	0.06	0.004021448

The above results are not adjusted for radiant power that hits the extrusion.
Other notable features:

- LED light output appears to saturate.
- Response to blue appears dominant.
- Response to UV appears to be very small.

Attempt to quantify differences

In order to quantify the difference between the response of the module/fiber/detector system I attempt to quantify the radiance, or more accurately the photon flux by measuring the current from a 5mmx5mm APD illuminated by the various light sources used above. Given that the APD QE varies by only about 10% over most of the wavelengths of interest, the current in the APD is a measure of the integral photon flux. I estimate an area factor determined by whether the source illuminates the entire APD surface, or if it is bigger than the APD surface. For LEDs and the lasers the majority of the light from the source was intercepted by the APD, so they have an area factor of about 1. The others have an area factor of the ratio of the illuminated area to the APD area, a maximum of 32. Some have intermediate values if the source is not constant over the entire area, or does not illuminate the entire area. These values are probably accurate to about a factor of two. The product of the Bare APD current and the area factor is calculated as the ~radiance factor. I then calculate the ratio of the light-dark signal to the radiance factor to determine the relative sensitivity of the system to the type of light source.

By this measure the most effective source for looking for light leaks is the blue LED. It is about 10X more effective than any other source. This is not surprising, since the blue light has a high probability of being absorbed by the fiber and captured as a signal. There is relatively little response to UV light, as this is probably absorbed by the PVC. In the visible spectrum, red light has the smallest effect, about 200x smaller than blue, and 10x smaller than green. The green-red difference is likely a difference in scattering probabilities, and also quantum efficiency of the phototube.

Lamp	dark	light	light-dark	rel	Bare APD current	Area factor	~radiance factor	Signal Radiance factor
Leon	0.08	1400	1399.92	9.38E+01	1700	32	54400	2.57E-02
fluor tube @2cm	0.08	432	431.92	2.89E+01	980	32	31360	1.38E-02
60W incand	0.08	400	399.92	2.68E+01				
Blue Led 50mA	0.05	200	199.95	1.34E+01	940	1	940	2.13E-01
26W CF	0.08	195	194.92	1.31E+01	1300	32	41600	4.69E-03
Blue Led 25mA	0.05	100	99.95	6.70E+00	540	1	540	1.85E-01
flashlight	0.08	70	69.92	4.69E+00	2300	16	36800	1.90E-03
60W bug light	0.05	64	63.95	4.29E+00	4500	32	144000	4.44E-04
AA maglight	0.05	35.5	35.45	2.38E+00	4000	16	64000	5.54E-04
fluor tube @2m	0.08	15	14.92	1.00E+00	24	32	768	1.94E-02
indirect sun	0.08	10.8	10.72	7.18E-01				
75W incand blacklight	0.05	6	5.95	3.99E-01	3500	32	112000	5.31E-05
red laser2	0.05	2.2	2.15	1.44E-01	3800	1	3800	5.66E-04
weak sun	0.08	1.1	1.02	6.84E-02				
red laser1	0.08	0.5	0.42	2.82E-02	800	1	800	5.25E-04
Green Led 75mA	0.05	0.42	0.37	2.48E-02	45	1	45	8.22E-03
Green Led 50mA	0.05	0.4	0.35	2.35E-02	30	1	30	1.17E-02
Green Led 25mA	0.05	0.25	0.2	1.34E-02	15	1	15	1.33E-02
Red Led 50mA	0.05	0.22	0.17	1.14E-02	120	1	120	1.42E-03
Red Led 80mA	0.05	0.2	0.15	1.01E-02				
Red Led 25mA	0.05	0.16	0.11	7.37E-03	67	1	67	1.64E-03
4WUV254nm	0.05	0.11	0.06	4.02E-03	40	32	1280	4.69E-05
4WUV365nm	0.05	0.11	0.06	4.02E-03	120	32	3840	1.56E-05

More Testing with an APD

Upon discovering that the fiber does indeed scatter and trap some red light, I worried that the effect I was seeing would be more pronounced when viewed with an APD due to the much higher quantum efficiency of the APD relative to a PMT at these frequencies. Indeed the APD is much more responsive to the red light, down about a factor of 20 from the blue LED, but not the factor of 400 seen with the PMT testing.

Lamp	dark	light	light-dark	Relative	Bare APD current	Area factor	~radiance factor	Signal Radiance factor	Relative
Leon	20	22	2	1.00E+00	1700	32	54400	3.68E-05	1
Laser	20.1	20.2	0.1	5.00E-02	3800	1	3800	2.63E-05	0.715789
Blue Led 50mA	20.1	20.5	0.4	2.00E-01	940	1	940	4.26E-04	11.57447

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Tests of light sleeves

Light Source	Bare APD	Yellow filter APD	Red Filter APD	Bare Module	Yellow Filter Module	Red Filter Module
Leon	1400	550	30	1.2	0.25	0.01
laser	3000	2200	220	0.1	0.1	0.01
Blue LED 50ma	940	1.7	0	0.2	0	0

There was some hope initially that blocking the short wavelength emissions from the room lights that we would be able to dramatically reduce the sensitivity of the system to ambient light. Unfortunately, this was before the realization that even long wavelength light gets trapped in the fiber, despite what one would think from Snell's law.

In order to test the effectiveness of the light sleeves at reducing the light leak signal I tested two types of sleeves with 3 types of lamps. The sleeves were a "gold" sleeve, which has relatively good transmission, and a "red" sleeve which is quite dark, and attenuates all wavelengths of light strongly. The table above shows the "APD" signals in the 5mmx5mm APD with the bare light source and each of the filters and the module response in the 2cmx4cm area to the bare lamps and with the filters.

The effectiveness of the light shields is slightly greater than the reduction in light intensity if there is a blue component in the source. The "Leon Light" source showed a reduction in intensity of a factor of 3 and 50 with the yellow and red filters respectively, but showed reductions of module signals by factors of 5 and 100. The data for the red laser module signals show that they are attenuated by factors proportional to their APD signals.

Unfortunately the response to ambient light for the APD module system is proportional to intensity, even for short wavelengths. This means that having a lighting system that is sufficiently intense for installation is likely to be problematic, without regard to the wavelength for thinner (<4mm) extrusions. It could always be worse, so we should try to choose lights that have less blue, but eliminating the blue components with filters is not sufficient, and probably not worth the trouble.

Conclusions

- The system is most sensitive to blue light that can be shifted by the fiber fluor. For wavelengths absorbed by the fluor they are approximately 20x more problematic than other wavelengths.
- In spite of what Snell's law tells us, the fiber will trap incident light of other wavelengths, but with much lower probability, about 20x. The suspicion is that it does so by scattering the photons, some of which then end up scattered into paths that are trapped. This implies that filtering is not a sufficient solution
- The APD system is about 20x more sensitive to red light than a PMT system due to the flat quantum efficiency.
- The measured attenuation lengths vary from 0.15 to 0.19mm for various samples of PVC.
- For typical lighting intensities approximately 20 attenuation lengths of material are required to reduce the induced dark current to less than 10% of the typical APD dark current, implying a required thickness of 3.0 to 3.8mm.